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FLIGHT VARIABLES AFFECTING FUEL-VAPOR LOSS FROM A FUEL TANK

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

MEMORANDUM REPORT

for the

Army Air Forces, Air Technical Service Command

FLIGHT VARIABLES AFFECTING FUEL-VAPOR LOSS FROM A FUEL TANK

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SUMMARY

Tests were conducted to determine the effect of several flight variables and several types of fuel agitation on fuel-vapor loss from a fuel tank during flight. Data were obtained from simulated-flight tests, in which the effects of rate of climb, altitude, initial fuel temperature, weathering of fuel, and fuel agitation were investigated; and a correlation between the simulated-flight and actual-flight data was established.

The following conclusions were reached from the data obtained from the simulated-flight tests using AN-F-28, Amendment-2, fuel:

1. Fuel-vapor loss increased linearly with altitude beyond a critical altitude. Some small losses, however, occurred before the critical altitude was reached.

2. An increase in the initial fuel temperature above 70° F markedly increased fuel-vapor loss.

3. The rate of fuel-vapor loss increased with an increase in the rate of climb but the loss to any given altitude increased only slightly with an increase in the rate of climb of from 1000 to 4000 feet per minute. (The losses due to fuel foaming over at the higher rates of climb when the fuel tank is filled close to its capacity were not investigated.)

4. The rate of fuel-vapor loss was greatest during the climb portion of the flight and was very small during the constant-altitude flight.

5. The rate of fuel-vapor loss after the end of the climb period increased with altitude but the loss during the constant-altitude portion of the flight was small in comparison with the loss during the climb.

6. Mechanical mixing of the fuel similar to that produced by a submerged booster pump increased fuel-vapor loss, particularly during the constant-altitude portion of the flight.

7. Normal vibration in the wings and fuselage of the airplane during flight had little or no effect on fuel-vapor loss.

8. Sloshing of the fuel in the fuel tank similar to that produced by airplane rocking markedly increased fuel-vapor loss.

9. Weathering of the fuel by successive flights showed that fuel-vapor loss decreased with each succeeding flight.

10. The amount of fuel-vapor loss obtained during simulated-flight tests was in close agreement with the amount obtained during an actual-flight test.

INTRODUCTION

The fuel-vapor loss occurring through the vent of an aircraft fuel tank during flight has become of great importance with the advent of high-altitude, long-range military aircraft. This loss represents an increase in the fuel consumed during flight and results in a reduction of the cruising range or of the load-carrying capacity of the airplane.

The physical properties of fuels and the basic concepts pertaining to fuel vaporization have been investigated in connection with the vapor-locking of aircraft fuel systems, particularly by Dr. O. C. Bridgeman and his coworkers under the Coordinating Research Council and W. H. Curtis and R. R. Curtis of Thompson Products Inc. Information is still lacking, however, as to the effect of flight variables on fuel-vapor loss for a predetermined flight path.

This report presents the results of a series of simulated-flight tests conducted at the NACA Cleveland laboratory at the request of the Army Air Forces to determine the effects of flight variables, such as rate of climb, altitude, initial fuel temperature, fuel agitation, and fuel weathering on the fuel-vapor losses from a fuel tank. Each variable was studied independently, all other variables being held constant during each series of tests.

The simulated-flight tests were conducted with a small fuel tank on a bench-test installation to facilitate instrumentation and handling of the equipment during the tests. Flight tests were conducted with a similar installation in a twin-engine airplane to correlate the simulated-flight data with actual-flight data.

APPARATUS

Simulated-Flight Installation

By means of a simulated-flight bench-test installation (fig. 1), the fuel was subjected to conditions simulating those encountered during the flight of an airplane from the ground to a predetermined altitude. This installation consisted essentially of a fuel tank evacuated by vacuum pumps to produce a predetermined flight path.

The drum-type fuel tank was 10 inches in diameter and 15 inches in height (inside dimensions). The cylindrical portion of the tank was made of transparent plastic 1/4 inch thick and the ends were made of transparent plastic 1/2 inch thick. The tank was completely covered with felt insulation 1/2 inch thick. The tank was evacuated by three vane-type vacuum pumps, each with a capacity of 9 cubic feet per minute, connected in parallel. The vent line between the pumps and the tank was a reinforced flexible hose $1\frac{1}{8}$ inches in inside diameter and 5 feet in length. A solenoid valve was placed in the vent line just before the pumps. The loss of fuel was indicated by a balance having a dial of 2-pound range graduated in 0.01-pound units.

Representative temperatures at various levels within the tank were measured by five thermocouples spaced at $3\frac{1}{4}$-inch vertical intervals with the lowest thermocouple located 1/2 inch from the bottom of the tank. These thermocouples, along with two others that measured the heating-water and ambient-air temperatures, were connected to a self-balancing potentiometer through a selector switch.

The fuel vapor leaving the tank could be condensed by a fuel-vapor condenser consisting of a 6- by 9-inch temperature regulator, manufactured to Air Corps Specification No. 95-28139, and having the ends modified to fit in the vent line. The temperature within the fuel-vapor condenser was maintained between -20° and -60° F by circulating chilled kerosene at the rate of 3 gallons per minute through the passages around the tubes. By means of the fuel-vapor condenser it was possible to maintain higher rates of climb to increased altitudes than could be obtained with the vacuum pumps alone.

Changes in pressure experienced by an airplane climbing from the surface of the earth to a certain altitude at various rates of climb were simulated in the installation by means of a flight-path control. This control consisted of a vertical drum, rotating at a constant speed of 0.1 rpm, to which charts of the desired flight pattern (pressure altitude plotted against time in min) were attached. The pressure within the fuel tank was measured by an absolute-pressure U-tube manometer mounted in front of the drum. The pressure changes experienced by an airplane climbing to altitude, therefore, could be produced in the tank by manually controlling the air-bleed valves in the vent line so that the level of the mercury column in the open leg of the manometer followed the predetermined flight path on the chart. The open leg of the manometer was calibrated to eliminate the possibility of errors due to differences in the bore between the legs of the manometer. For this reason all altitudes referred to in this report are pressure altitudes.

The AN-F-28, Amendment-2, fuel used during both the simulated-flight tests and the actual-flight tests was drawn from the general laboratory supply and stored in the test room in a 55-gallon drum. Fuel was withdrawn from the drum as required by displacing it with water. (See fig. 1.) During the simulated-flight tests the fuel passed directly from the drum through a 9- by 9-inch temperature regulator before it entered the tank. The temperature regulator, built to Air Corps Specification No. 28141, was mofified to provide for the circulation of water at 120° F through the tubes.

Flight Installation

The flight tests were conducted in a twin-engine airplane with the cabin modified to accommodate equipment similar to that of the bench-test installation. In order to reproduce the laboratory conditions, a tank and a balance similar to those used in the bench tests were installed in the airplane. (See fig. 2.) The tank was vented to the atmosphere through an 84-inch length of reinforced flexible tubing of $1\frac{1}{8}$-inch inside diameter connected to an opening in the cabin window. A 2-inch gate valve was located in the vent line 34 inches from the tank. The temperatures at five points within the tank were measured by resistance-bulb temperature indicators located at $3\frac{1}{4}$-inch vertical intervals, with the lowest indicator located 1 inch from the bottom of the tank. These resistance bulbs, as well as one located in the vent line 5 inches above the top of the tank, were connected to dial temperature indicators in the instrument panel. Pressure measurements were obtained immediately outside the opening of the vent line to the atmosphere, in the vent line, and at the top of the fuel tank. These pressures were recorded as a pressure differential with reference to atmospheric pressure.

PROCEDURE

Simulated-Flight Tests

The procedure followed was similar for each simulated-flight test conducted, during each series of tests, all of the conditions with the exception of the variable being studied were held constant. The simulated-flight test taken as the standard was of 90-minute duration and consisted of a climb at the rate of 2000 feet per minute to 30,000 feet and level flight at this altitude to the end of the test.

The fuel and water in the sealed storage drum were thoroughly mixed before each test and the mixture was then allowed to separate for 10 minutes. The temperature of the water circulating through the temperature regulator was then adjusted to approximately 120° F in all tests except those in which the effect of initial fuel temperature was investigated. With the solenoid valve in the vent line closed, 15 pounds of fuel were transferred from the storage drum through the temperature regulator to the fuel tank; the temperature of the fuel entering the tank was approximately 110° F. In order to adjust the temperature of the fuel to 110° F ±0.5° F, hot or cold water was circulated through the coils in the tank and, at the same time, the fuel was intermittently agitated by an electrically driven propeller near the bottom of the tank. The pressure within the tank was maintained at atmospheric pressure during the filling operation only by means of a small drain cock in the vent line.

With the vacuum pumps operating, the test was started by simultaneously opening the solenoid valve in the vent line and starting the drum of the flight-path control to which a chart of the desired flight path had been attached. The balance dial reading and the temperatures indicated by the thermocouples were recorded just before the beginning of the test, at 1-minute intervals from 1 to 20 minutes, at 2-minute intervals from 20 to 30 minutes, and at 5-minute intervals from 30 minutes to the end of the test. A sample of the fuel was obtained from the fuel tank before and after each test for analysis by the A.S.T.M. distillation method.

Flight Tests

The actual-flight tests followed essentially the procedure used in the simulated-flight tests. In these tests the tank was filled with $16\frac{1}{2}$ pounds of fuel and the vent opening was sealed. The tank was then installed in the airplane and the weight rechecked before a fuel sample was withdrawn. With the valve in the vent line closed, the temperature of the gasoline was raised to approximately 110° F by circulating water at a temperature of 130° F through the coils. When the fuel had reached the desired temperature, a second fuel sample was obtained and the tare weight and the balance dial reading were recorded.

The actual-flight path, with small unavoidable deviations, consisted of a climb at a rate of 1000 feet per minute to a 20,000-foot altitude, a climb at a rate of 650 feet per minute to a 26,700-foot altitude, a half-hour flight at this altitude, and a descent to the ground at 1000 feet per minute.

Flight data were recorded by photographing the instrument panel and balance dial at timed intervals during the test. Photographs were taken before leaving the hangar apron, just as the wheels of the airplane left the ground at take-off, every 2 minutes during the climb, every 4 minutes during the constant-altitude flight, and every 2 minutes during the descent until the wheels of the airplane again touched ground. A final photograph and a fuel sample were then taken with the vent closed and the engines turned off.

Tests were conducted on the simulated-flight installation simulating the same conditions that were encountered in the actual flight.

ACCURACY OF RESULTS

The accuracy of the test results was dependent upon the reproducibility of the test conditions. Variables affecting the reproducibility of tests were recognized but could not be effectively controlled during this investigation. The sources of error considered to be greatest were given special attention, but it was impossible to measure the quantitative effect of each source of error independently or to recognize which source of error contributed during any one test.

The greatest variation in test results was probably caused by air leaking into the tank through the joints and the seams of the tank. As the air leaked into the tank and passed out through the vent, it carried with it a quantity of fuel vapor which, depending upon the amount of air leakage, could appreciably affect the results of the test. The fuel tank was checked for leaks before and after each test and the results of the tests in which leakage was evident were discarded.

The accuracy of the potentiometer used to indicate temperatures may have had an effect on the test results. The potentiometer used had a random error of $\pm 1^\circ$ F plus a possible inherent error of ± 0.1 percent of the full-scale deflection of the instrument. With a range of 800° F, the potentiometer thus had a possible error of $\pm 1.8^\circ$ F. It was quite possible, therefore, that the initial fuel temperature could have varied between 112° F and 108° F at the beginning of each test, which would have resulted in a possible difference in total fuel-vapor loss of ± 0.350 percent.

Because of conditions beyond the control of the operator, the fuel often entered the tank at temperatures ranging from 105° F to 115° F instead of the desired temperature of 110° F $\pm 0.5^\circ$ F. Owing to this variation, it was necessary to adjust the temperature of the fuel by circulating hot or cold water through the coils and intermittently stirring the fuel with the submerged propeller. At propeller speeds as low as 100 rpm it was noted that bubbles were formed along the trailing edges of the propeller blades. The bubbles thus formed could be a result of air being released from solution in the fuel or of fuel vapor being formed because of a low-pressure area at the trailing edges of the propeller blades. The fuel-vapor loss during this period of the test was checked on several occasions and in each case was found to be negligible.

Inasmuch as the flight-path control was manually operated, the accuracy of the instrument depended on the skill of the operator. Despite all the precautions taken, therefore, the pressure within the tank could be controlled only to within ± 0.1 inch of mercury during the climb periods. During the constant-altitude portions of the tests, the pressure could be held to within ± 0.05 inch of mercury.

It was found that the fuel-vapor loss was also affected by the ambient-air temperature, despite the fact that the test tank was completely covered with 1/2-inch felt insulation. This effect was indicated by a series of tests during which the fuel tank was enclosed in a box and the temperature of the air surrounding the tank held constant at each of several predetermined temperatures. During the climb portions of the test when the highest rates of loss were experienced, the effect of the ambient-air temperature was not noticeable but it was readily evident during the constant-altitude portion of the simulated flight. A plot of the fuel-vapor loss occurring from the end of the climb to the end of the test against the average ambient-air temperature (fig. 3) indicates a linear variation of fuel-vapor loss with ambient-air temperature.

The chief differences between the actual-flight tests and the simulated-flight tests were in the methods of producing altitude pressure within the tank and the differences in ambient-air temperatures around the tank. In the simulated-flight installation, altitude pressures were produced directly within the tank; whereas, during the actual-flight test, altitude pressure existed at the opening of the vent line to the ambient-air pressure outside the airplane fuselage. The difference between the pressure inside the fuel tank and that of the outside atmosphere, however, was never greater than 0.06 inch of mercury during the actual flight. During the flight test the tank was covered with an additional layer of 1/2-inch-thick felt insulation in an effort to obtain the same rate of heat transfer at the lower cabin temperatures as was experienced during the simulated-flight test.

Erratic scale readings during the actual-flight tests were obtained as a result of the scale's being jarred at intervals owing to the roughness of the flight. At high altitude (26,700 ft) it was difficult to maintain level flight because the airplane was operating near its service ceiling; as a result, the balance dial oscillated during the interval of recovery after loss of altitude. During the first part of the descent from level flight at high altitude, the operating conditions were changing, thus causing the airplane to vibrate.

The effect of vent size, which is a flight variable in the actual airplane, did not enter into this investigation inasmuch as the pressure altitudes were reproduced within the tank and not at the vent outlet.

RESULTS OF SIMULATED-FLIGHT TESTS

The data obtained from a typical standard simulated flight are shown in figures 4, 5, and 6. Figure 4 shows the fuel-vapor loss, the average fuel temperature, and the average vapor temperature above the fuel as a function of the flight time. The rate of fuel-vapor loss plotted in figure 5 as a function of flight time was obtained by taking the slope of the fuel-vapor-loss curve of figure 4. The change in the fuel characteristics due to the simulated flight is shown in figure 6 where the A.S.T.M. distillation curves before and after the simulated flight are compared. A careful analysis of the two curves presented in figure 6 reveals that the greatest portion of the fuel lost is in the lower boiling-point region of the distillation curve.

Rate of Climb

For the rate-of-climb tests the fuel in the tank was subjected to simulated flights at rates of climb of 1000, 2000, and 4000 feet per minute to an altitude of 40,000 feet. The results of these tests (fig. 7) indicate that the rate of fuel-vapor loss is apparently a function of the rate of climb. Replotting the data with fuel-vapor loss as a function of altitude (fig. 8) indicates that, at any given altitude, loss increased only slightly with increased rate of climb for the rates tested (1/4 percent per 1000 ft/min between rates of climb of 1000 and 2000 ft/min; 1/8 percent per 1000 ft/min between 2000 and 4000 ft/min). The losses due to fuel foaming over at the higher rates of climb when the fuel tank is filled close to its capacity were not investigated.

Altitude

A linear variation of fuel-vapor loss with altitude above some critical altitude (the theoretical altitude at which fuel-vapor loss begins) is shown in figure 8. From the slope of the curve the following formula can be derived for predicting the approximate fuel-vapor loss for a climb to a given altitude:

$$L = \frac{Z - Z_c}{1.9}$$

where

L fuel-vapor loss, percent

Z altitude, in 1000 feet

Z_c critical altitude, in 1000 feet (intersection of linear portion of loss-against-altitude curve with base line, fig. 8)

Several simulated flights were conducted, each at the same rate of climb, but for each flight the climb ended at a different altitude, which was maintained for a period of time. Simulated altitudes of 10,000, 20,000, 30,000, and 40,000 feet were reached by a climb of 2000 feet per minute. The total flight time was 65 minutes. The results of this series of tests are presented in figure 9.

The fuel-vapor loss after the end of the climb period is presented in figure 10. The increase in the rate of fuel-vapor loss after the end of the climb period with increased altitude can be noted and was probably caused by any one or a combination of the following factors: (1) a short time was needed for the system to come to equilibrium at the new altitude pressure after the climb period; (2) the evaporation rate may have increased with decreased atmospheric pressure; and (3) if any air leaks were present, the error caused would have been magnified as the altitude was increased.

Initial Fuel Temperature

The effect of the initial fuel temperature on fuel-vapor loss was investigated by conducting several tests in which batches of fuel at initial temperatures of 110°, 90°, 70°, 50°, and 29° F were subjected to standard simulated flights.

Because fuel-vapor loss is a function of the fuel-vapor pressure, which in turn is a function of fuel temperature, decreasing the fuel temperature should reduce the fuel-vapor loss. (See fig. 11.) Replotting the data as fuel-vapor loss at the end of the climb against initial fuel temperature (fig. 12) indicates a rapid linear increase in fuel-vapor loss with increases in fuel temperatures above 70° F. The fuel-vapor loss during a climb to an altitude of 30,000 feet at initial fuel temperatures above 70° F, therefore, could possibly be predicted from the following equation derived from the slope of the curve of figure 12:

$$L = K (T - T_c)$$

where

L fuel-vapor loss, percent

T initial fuel temperature, °F

T_c temperature above which loss varies linearly with temperature (the intersection with the base line of the linear portion of the curve of fuel-vapor loss against initial fuel temperature, fig. 12), °F

K constant (0.13 percent per °F, from fig. 12)

This equation and figure 12 indicate that precooling of the fuel will appreciably reduce the fuel-vapor loss.

Weathering of the Fuel

The effect of weathering of the fuel on fuel-vapor loss was investigated by submitting the same tank of fuel to several successive standard simulated flights. The curves showing fuel-vapor loss plotted against flight time for three successive simulated flights are presented in figure 13. Replotting the data to show the total loss at the end of each simulated flight as a function of the number of flights (fig. 14) indicates a linear relation with the loss decreasing markedly for each successive simulated flight.

Fuel Agitation

Several types of fuel agitation experienced in an aircraft fuel tank during flight were individually reproduced during simulated flights and their effect on fuel-vapor loss was determined.

Vibration. - In order to simulate low-amplitude vibration within the range experienced in the wing and fuselage of an airplane during flight (reference 1), the fuel tank was vibrated vertically during a standard simulated flight by an air-operated vibrator attached to the tank. Vibrating the fuel tank at frequencies of 168 and 120 cycles per second at amplitudes of 0.0009 and 0.0018 inch, respectively, had little, if any, effect on fuel-vapor loss with no definite trend. (See fig. 15.)

Mechanical agitation. - In order to simulate the effect of the turbulence created by the propeller of a submerged fuel booster pump on fuel-vapor loss, a three-bladed propeller was installed in the fuel tank of the simulated-flight installation and the fuel-vapor loss during standard simulated flight was determined for several propeller speeds. The propeller, $2\frac{1}{2}$ inches in diameter and driven by a modified booster-pump motor, was located $3\frac{1}{2}$ inches above the bottom center of the tank. The propeller blades were set at an angle of 30° with the plane of rotation and were used to thrust the fuel downward in one series of tests and upward in a second series of tests. The results of the two series of tests (fig. 16) indicate that, for the range of speeds investigated, the fuel-vapor loss increases with speed irrespective of the direction of thrust. Plotting the fuel-vapor loss at the end of the standard simulated flight as a function of propeller speed (fig. 17) shows that the rate of fuel-vapor loss with speed for either direction of thrust is the same. This increase in fuel-vapor loss with increased propeller speed tends to substantiate the conclusion reached in reference 2 that agitation created by a propeller produces low-pressure regions along the trailing edge of the propeller blades and at the center vortex. The low-pressure regions produce vapors that should result in increased evaporation of the fuel with increase in propeller speed.

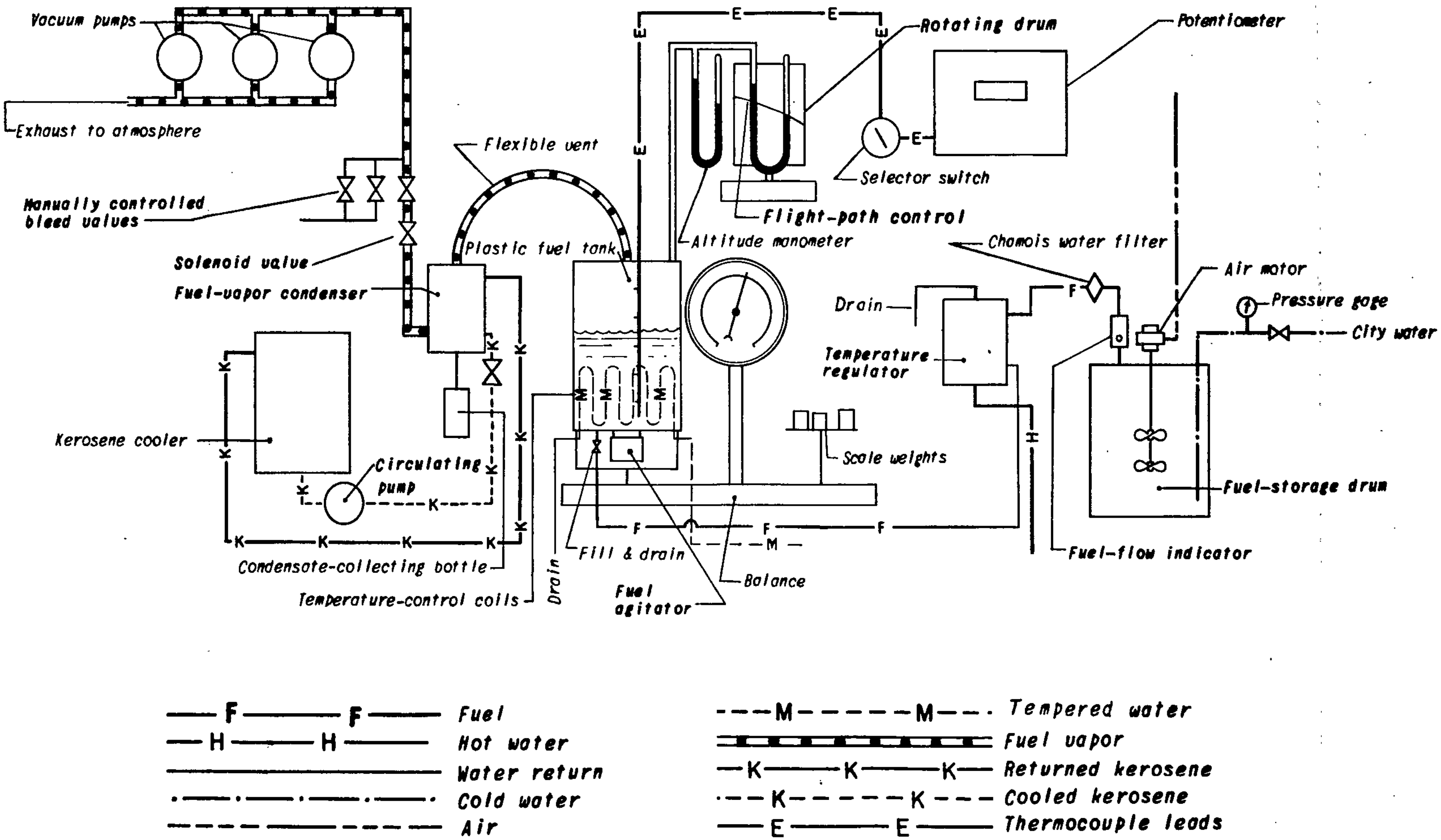

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Figure 1. - Diagrammatic sketch of simulated-flight bench-test installation.

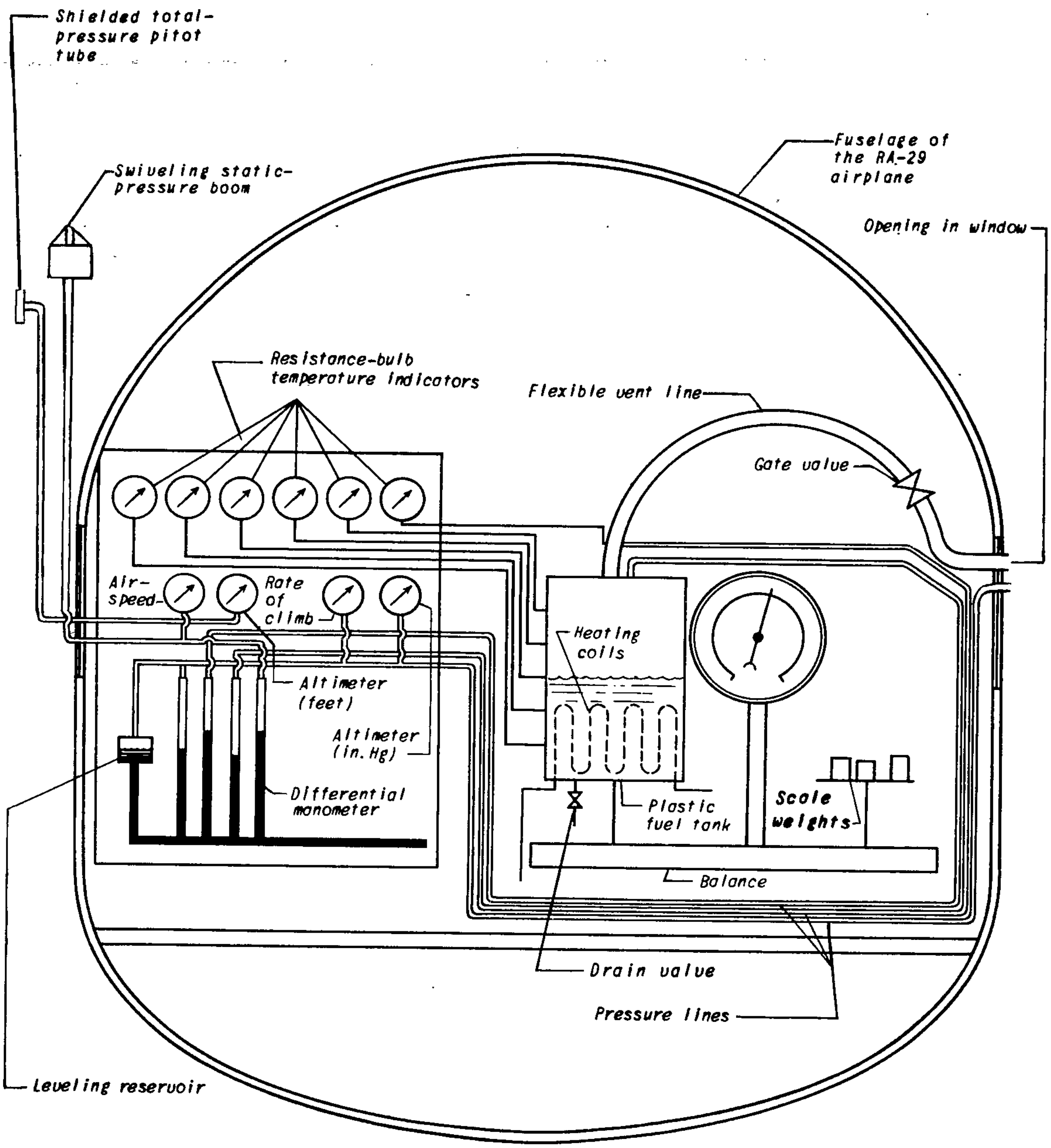

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Figure 2. - Flight-test installation.

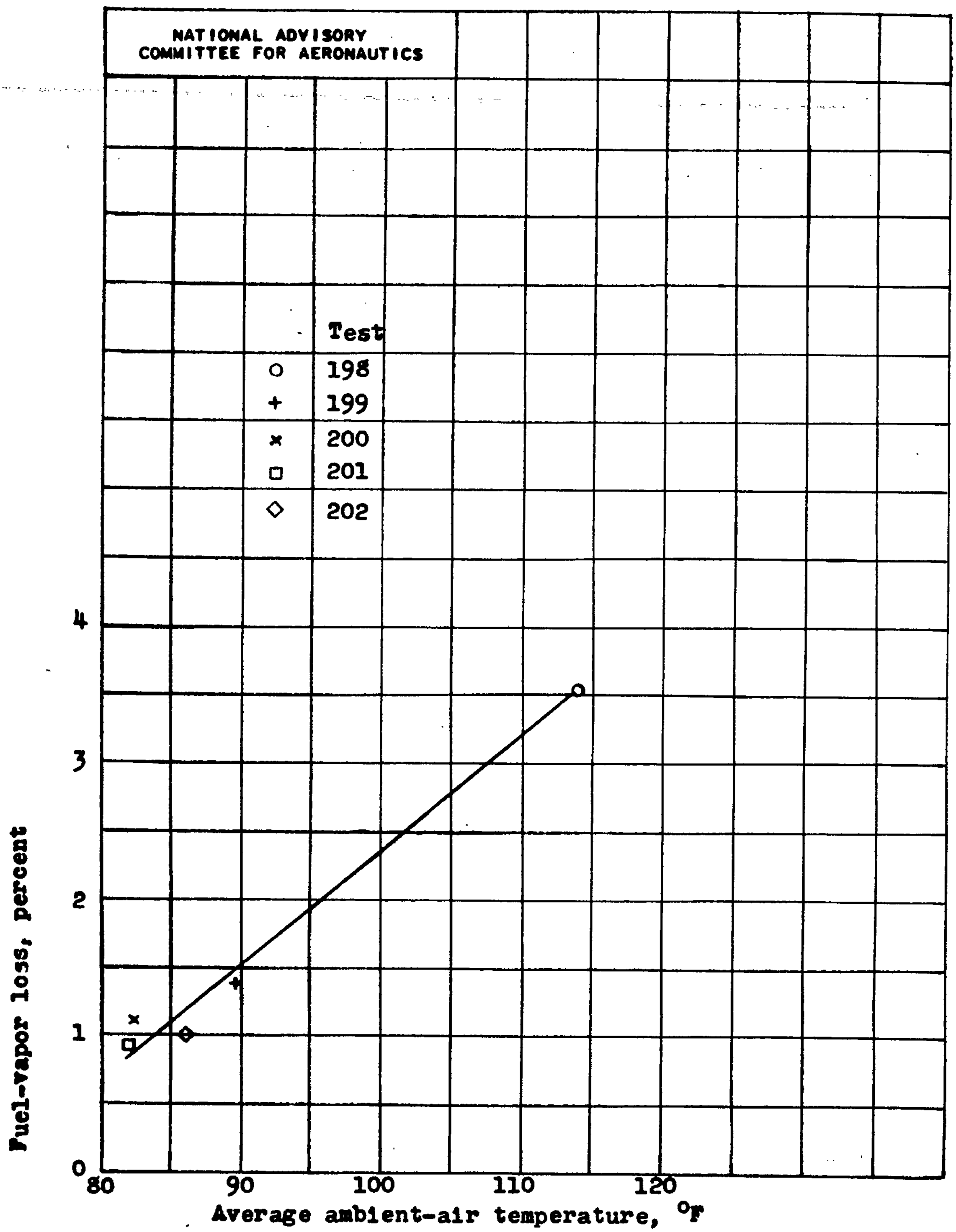


Figure 3. - Variation of fuel-vapor loss from the end of the climb period to the end of the standard simulated flight. with average ambient-air temperature.

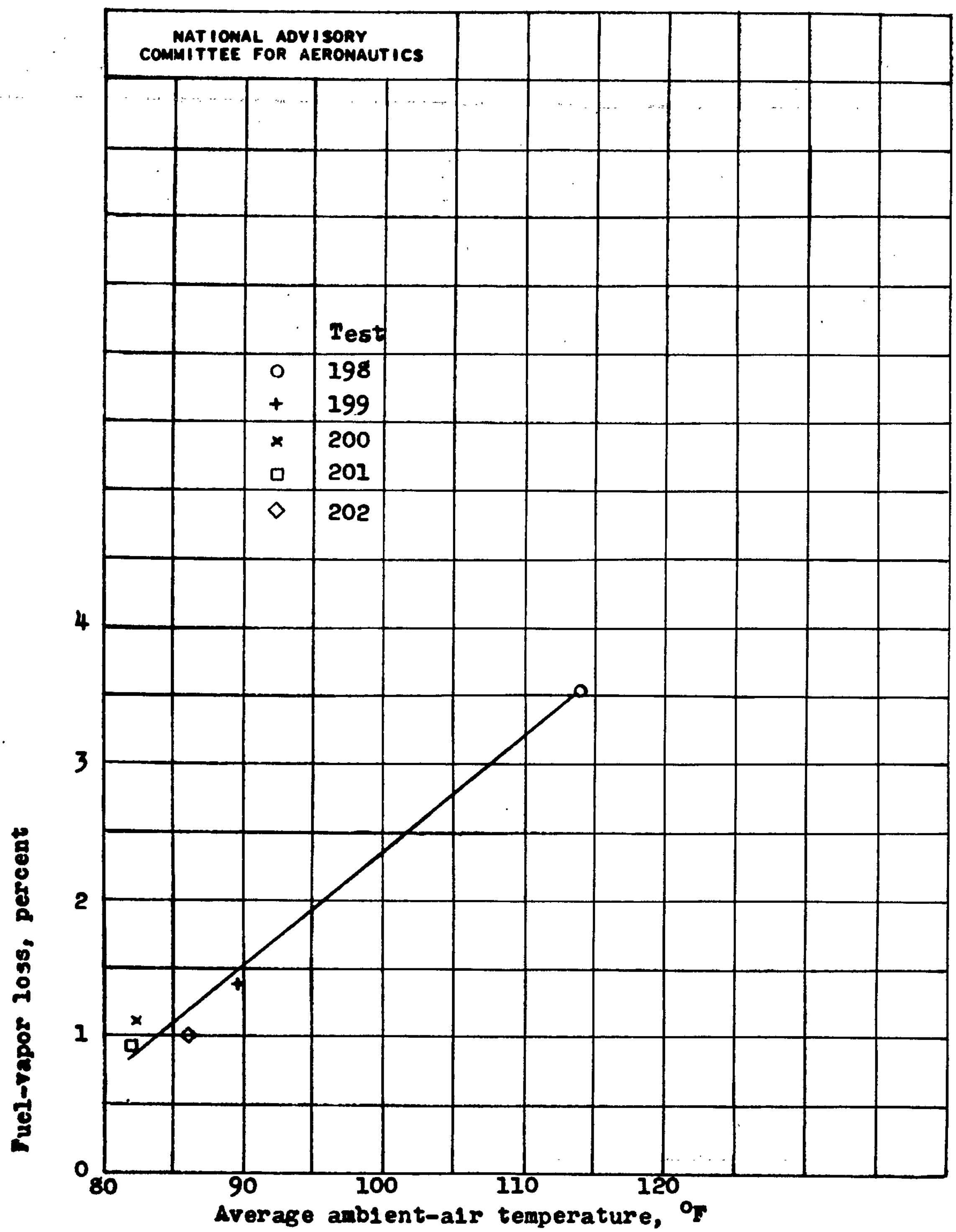


Figure 3. - Variation of fuel-vapor loss from the end of the climb period to the end of the standard simulated flight with average ambient-air temperature.

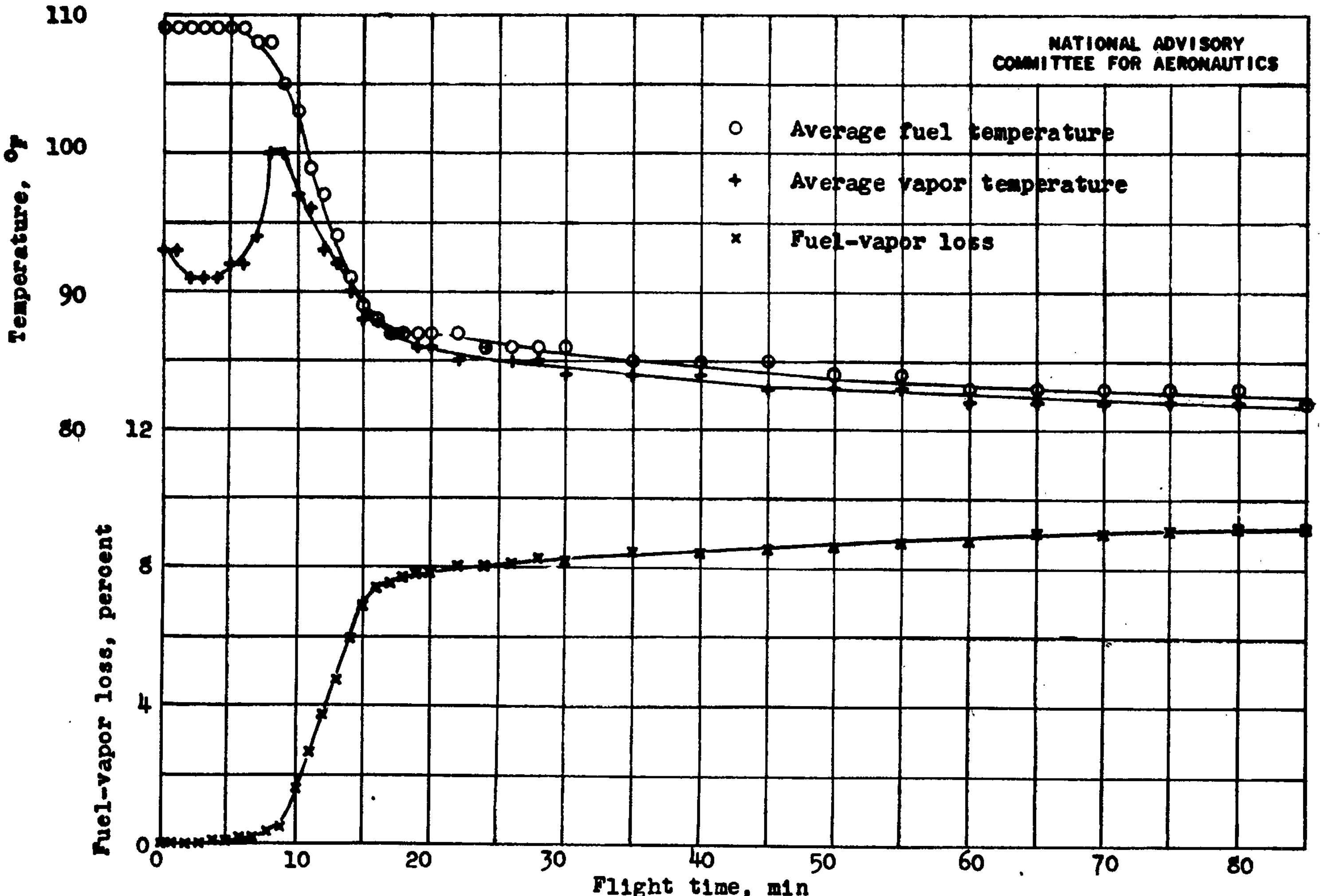


Figure 4. - Fuel-vapor loss, average fuel temperature, and average vapor temperature measured during a standard simulated flight. Test 67. Standard simulated flight consisted of a climb at 2000 feet per minute to an altitude of 30,000 feet with level flight at this altitude to end of test.

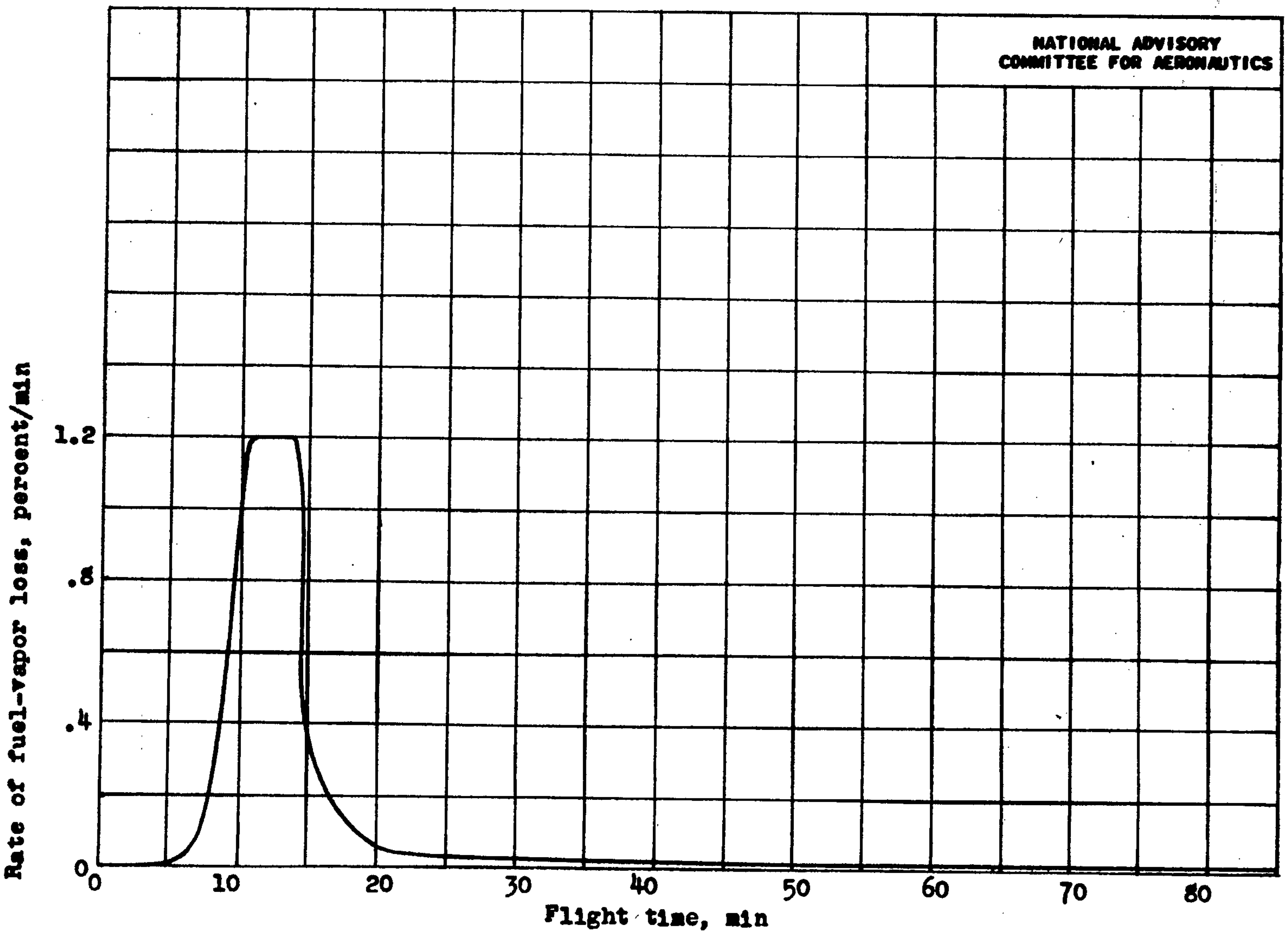


Figure 5. - Rate of fuel-vapor loss during a standard simulated flight. Test 67.

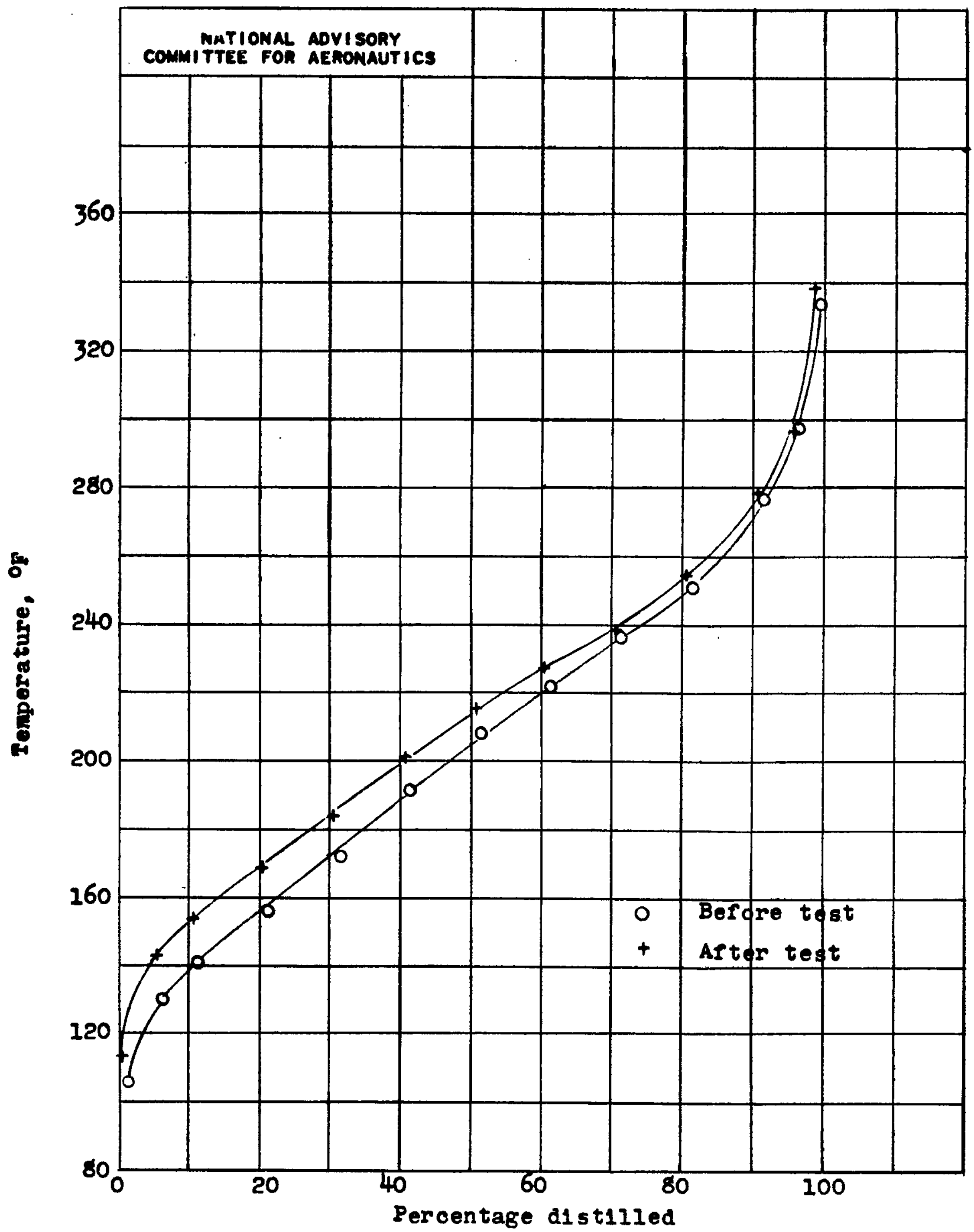


Figure 6. - A.S.T.M. distillation curves of the fuel before and after a standard simulated flight. Test 67.

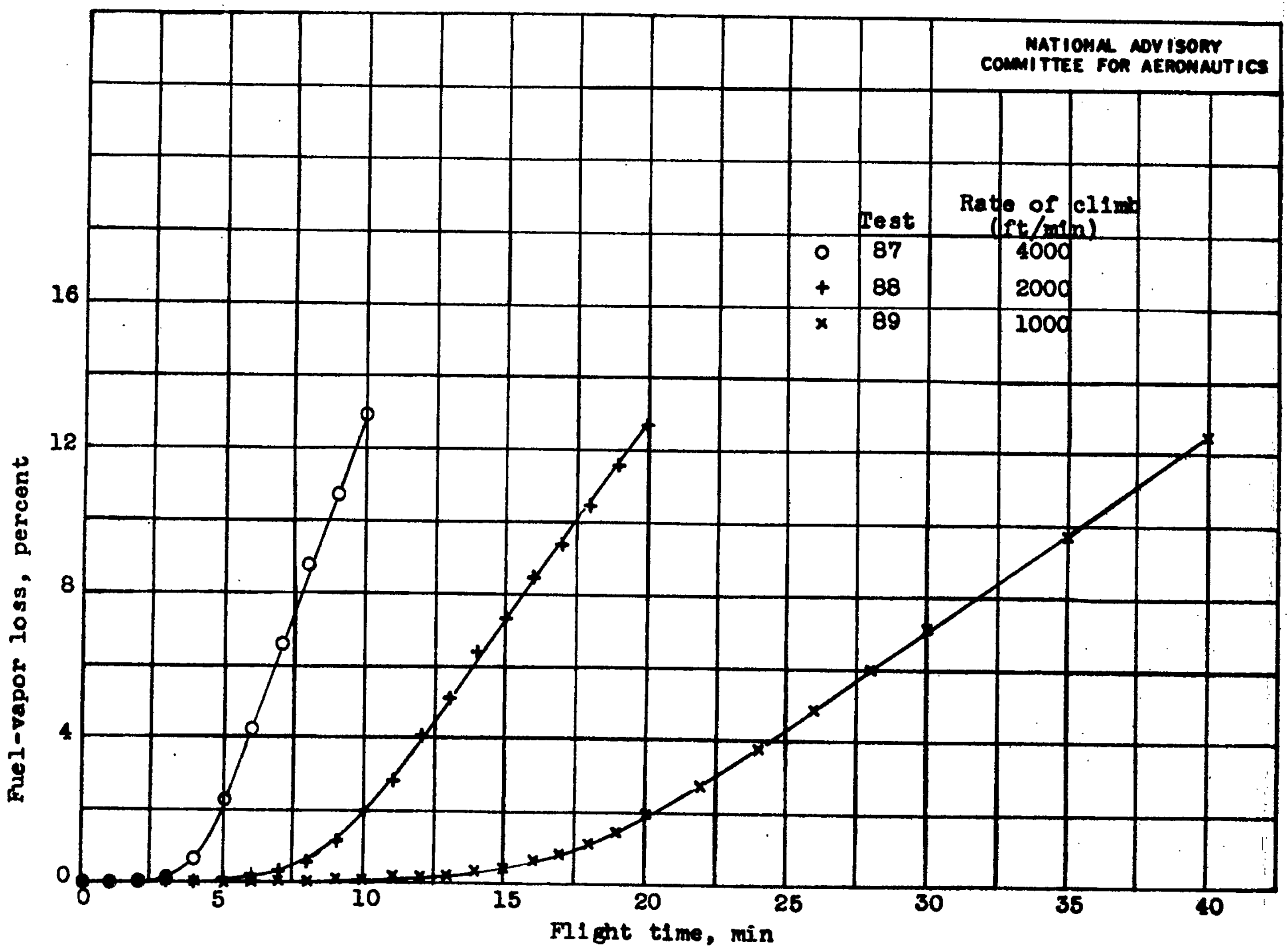


Figure 7. - Fuel-vapor loss during simulated flights to 40,000 feet at various rates of climb.

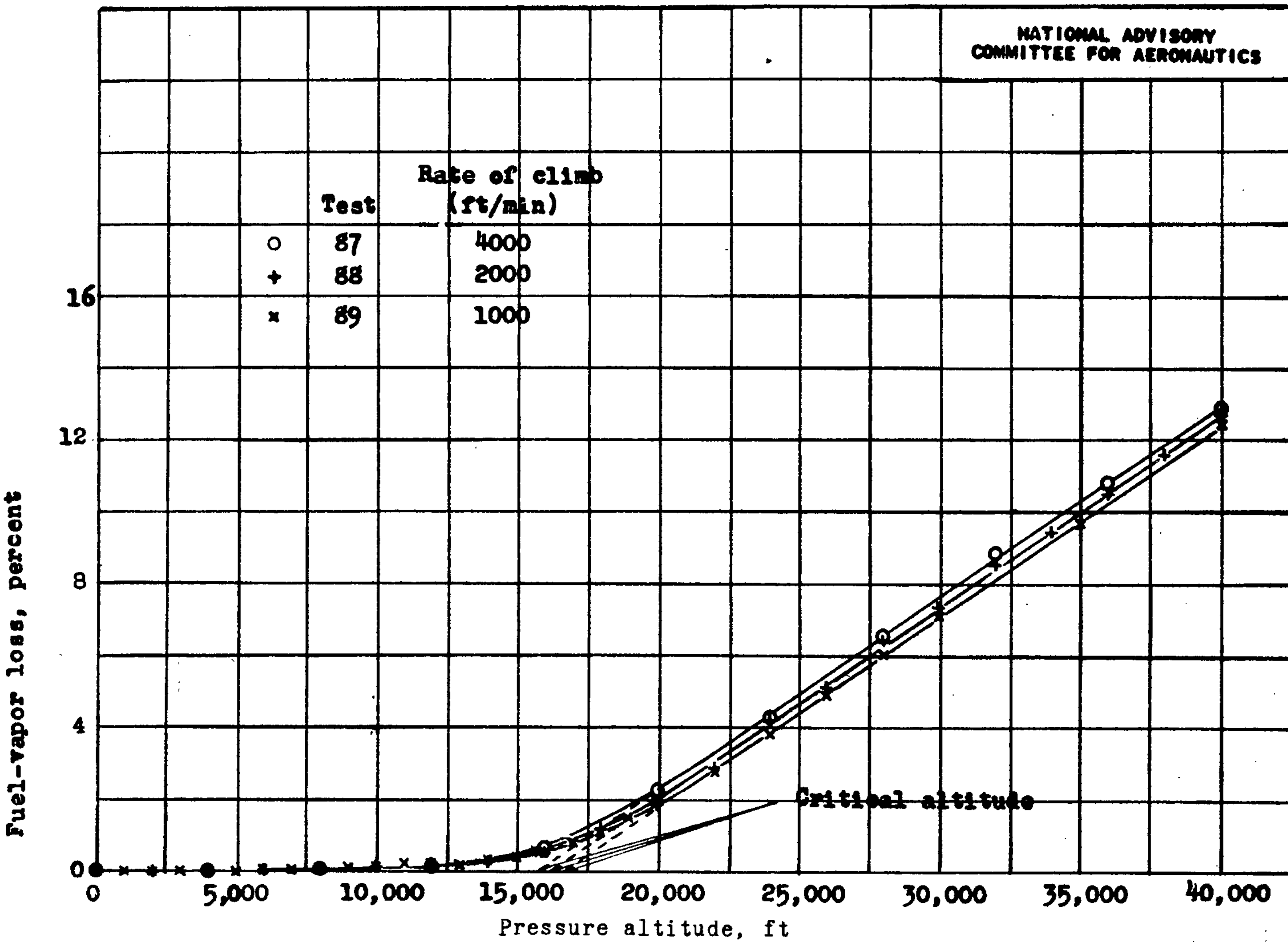


Figure 8. - Variation of fuel-vapor loss with altitude during simulated flights at various rates of climb.

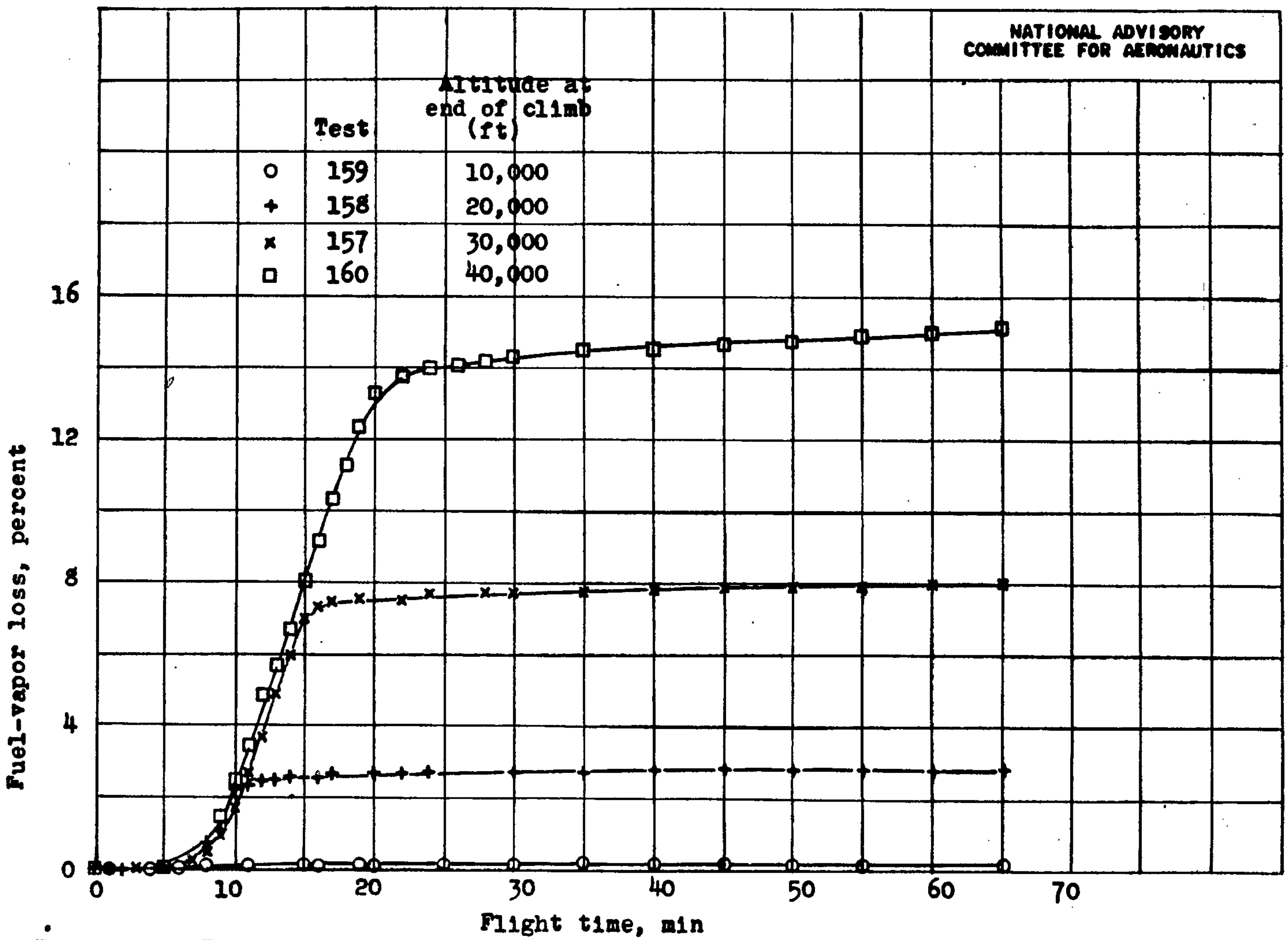


Figure 9. - Fuel-vapor loss during simulated flights to various altitudes. Rate of climb, 2000 feet per minute; altitudes after climb held constant to end of flight.

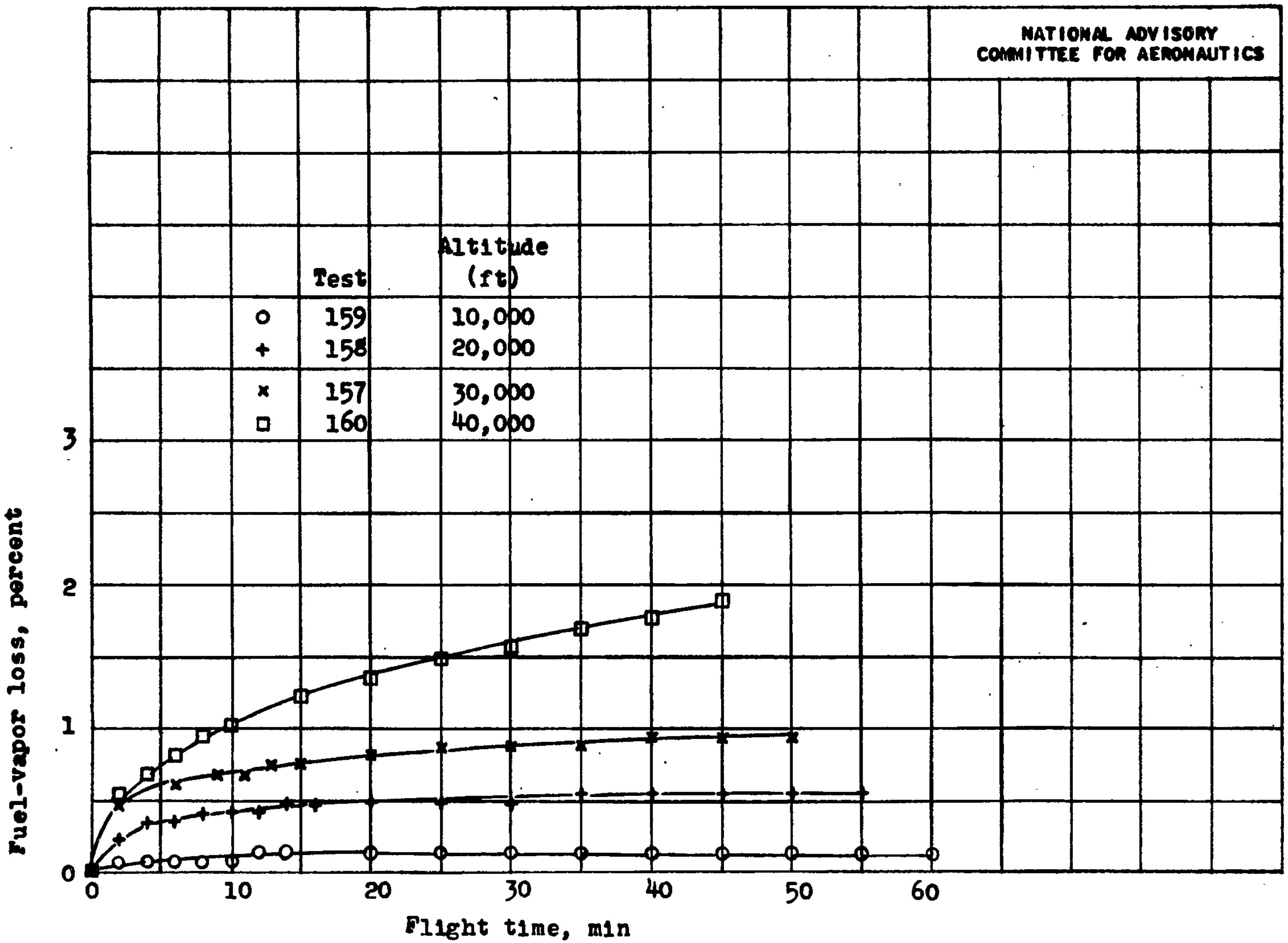


Figure 10. - Fuel-vapor loss during the constant-altitude portion of simulated flights. Altitudes attained by a constant rate of climb of 2000 feet per minute.

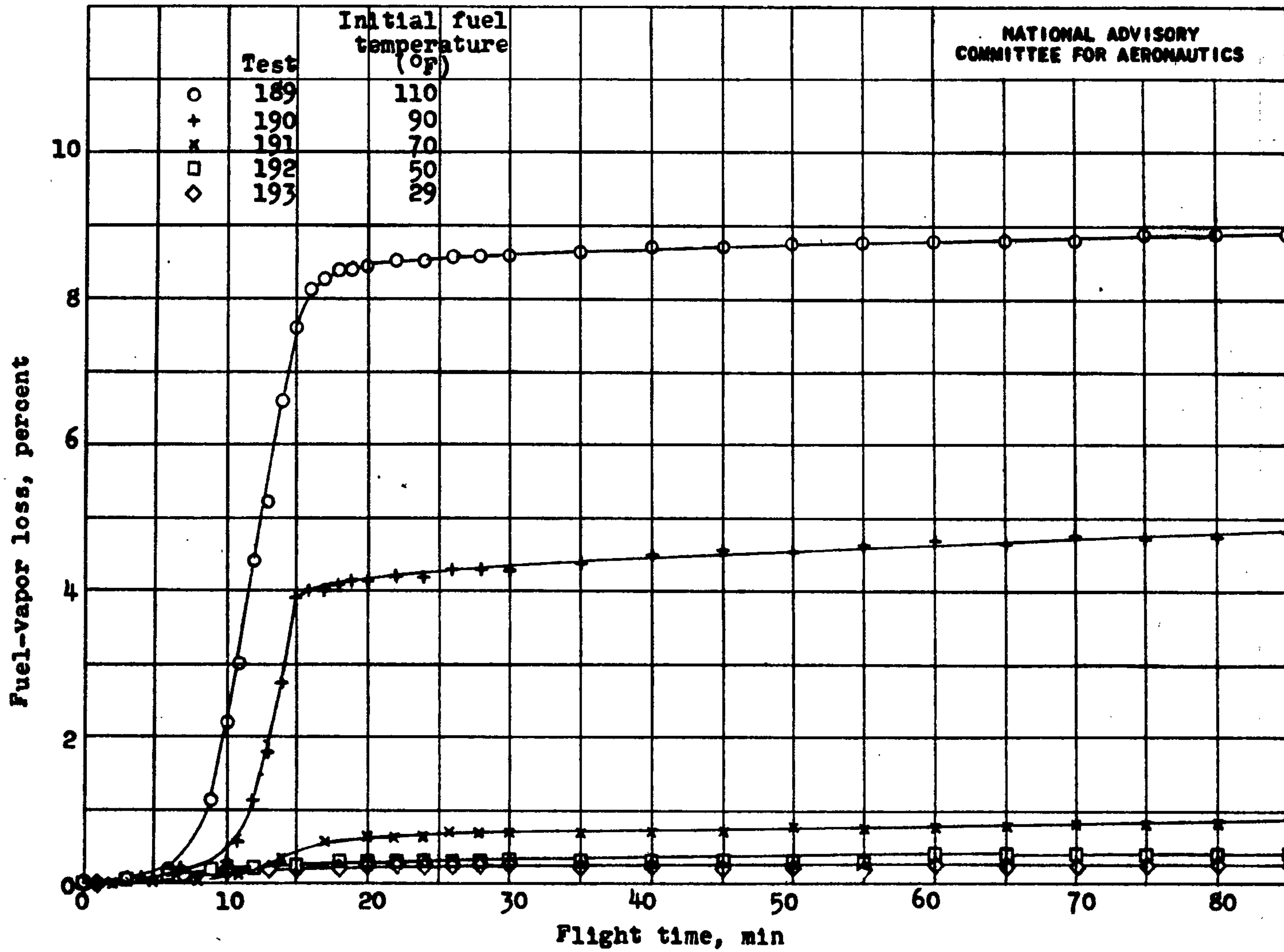


Figure 11. - Fuel-vapor loss during standard simulated flights with various initial fuel temperatures.

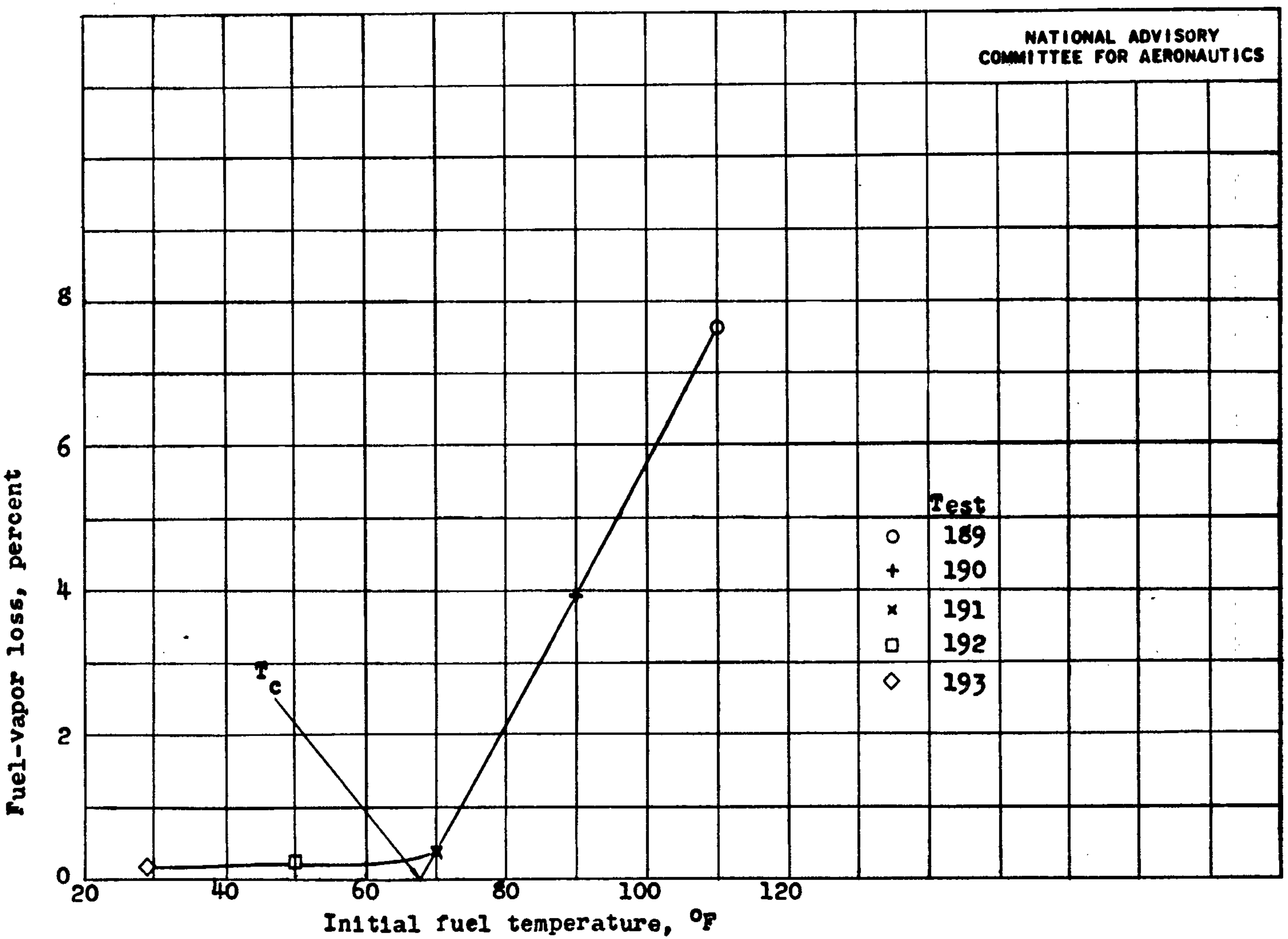


Figure 12. - Fuel-vapor loss at the end of the climb period for standard simulated flights with fuel at various initial fuel temperatures.

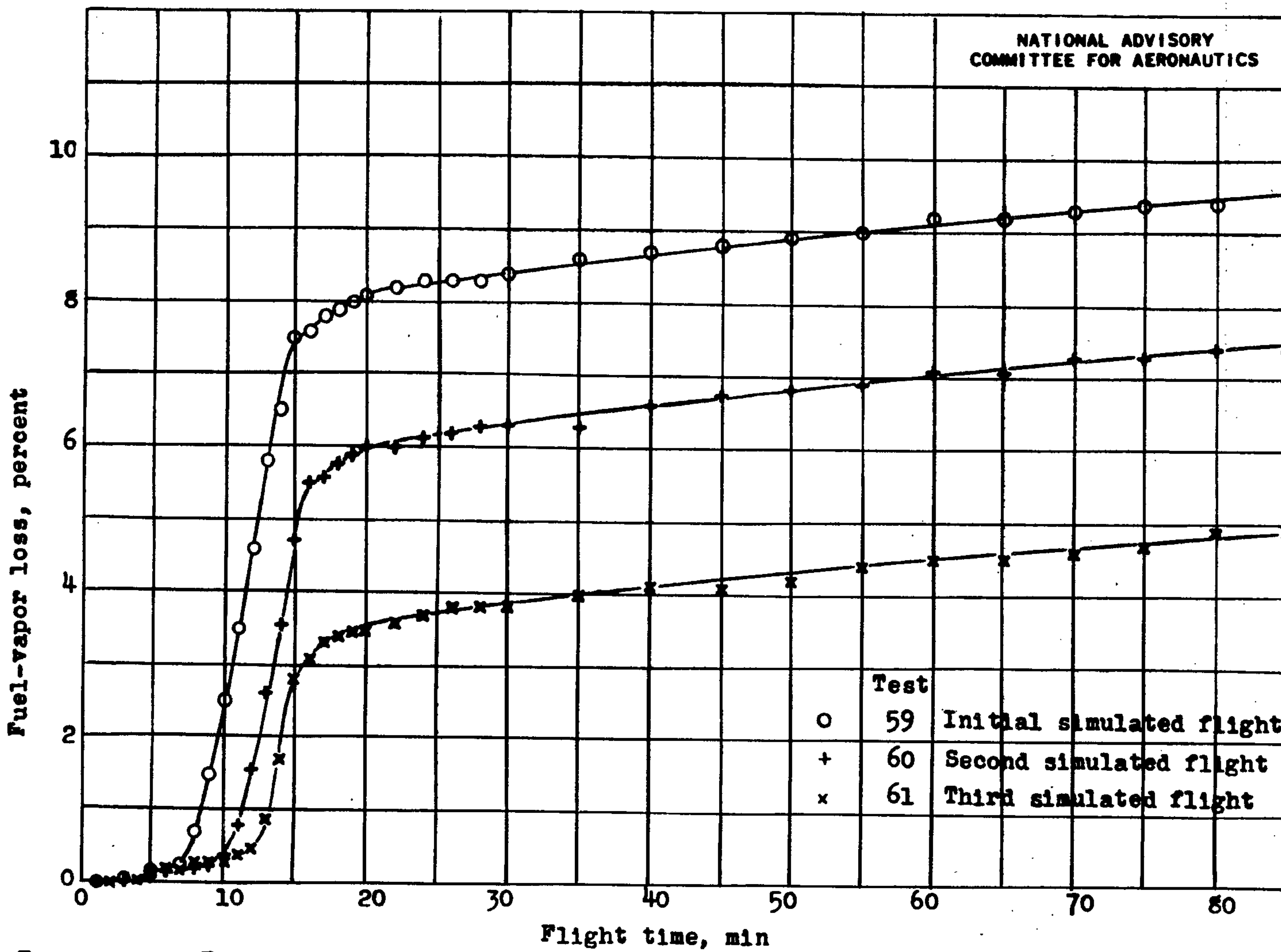


Figure 13. - Fuel-vapor loss during successive standard simulated flights with a given fuel sample.

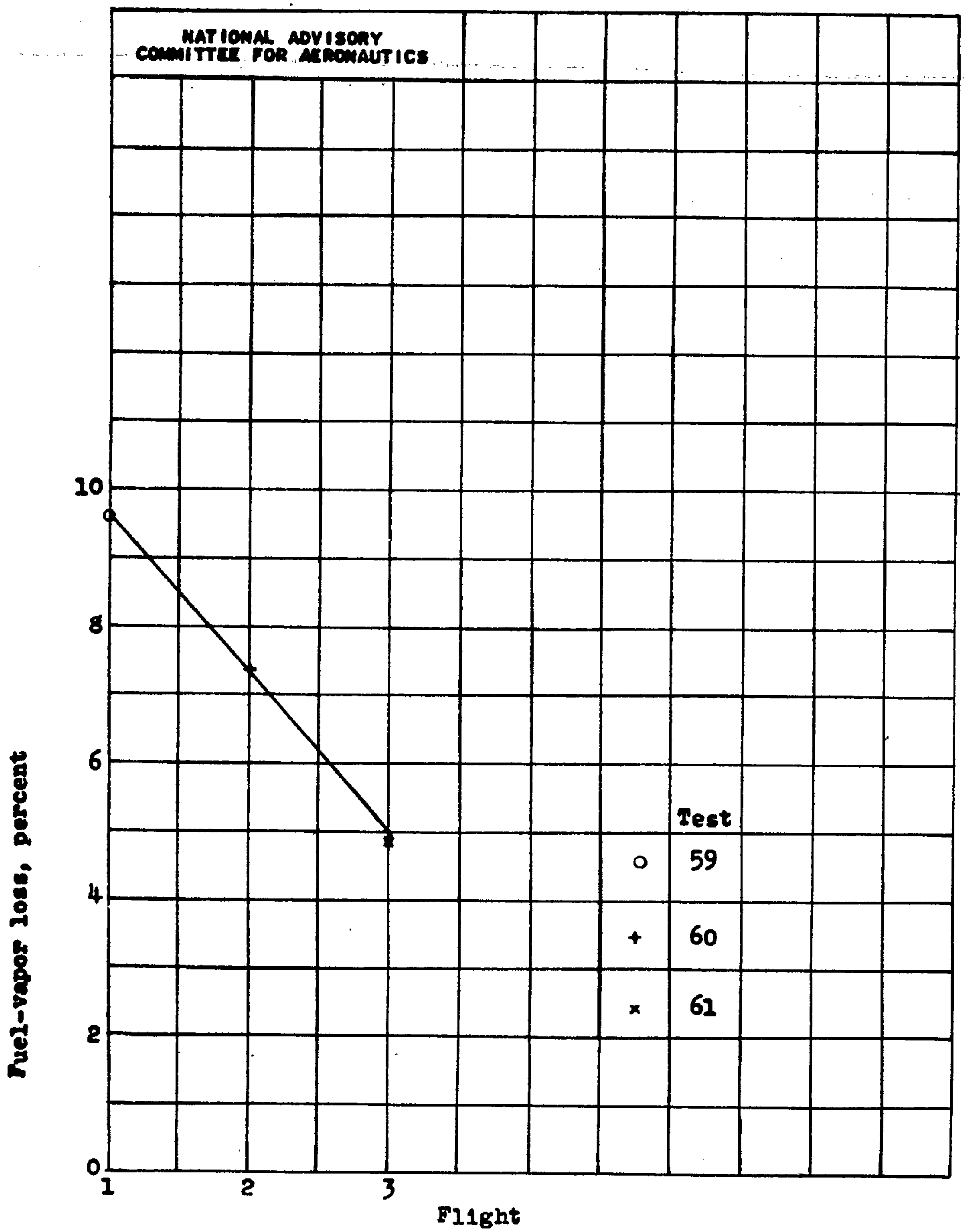


Figure 14. - Total fuel-vapor loss during successive standard simulated flights with a given fuel sample.

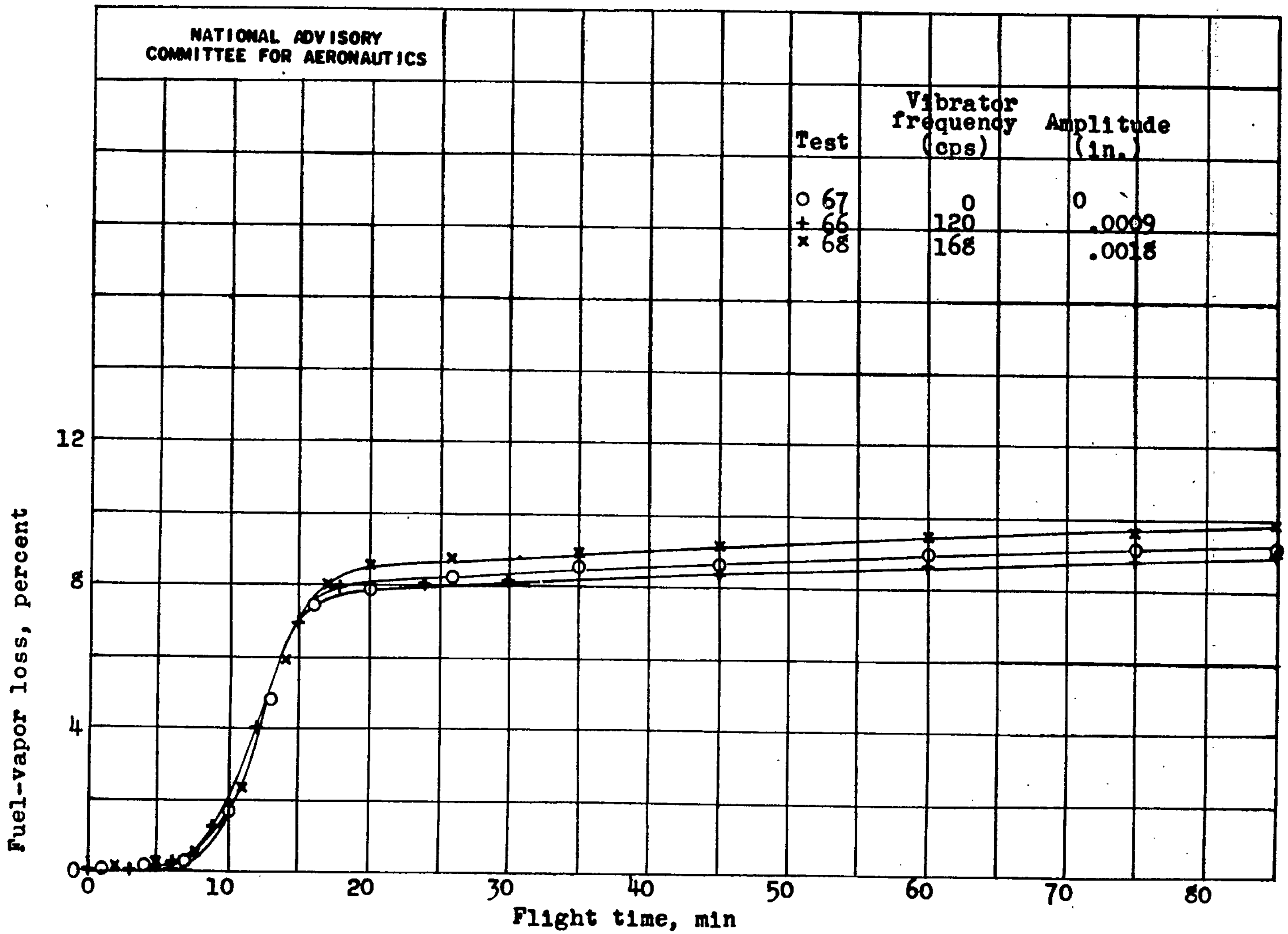
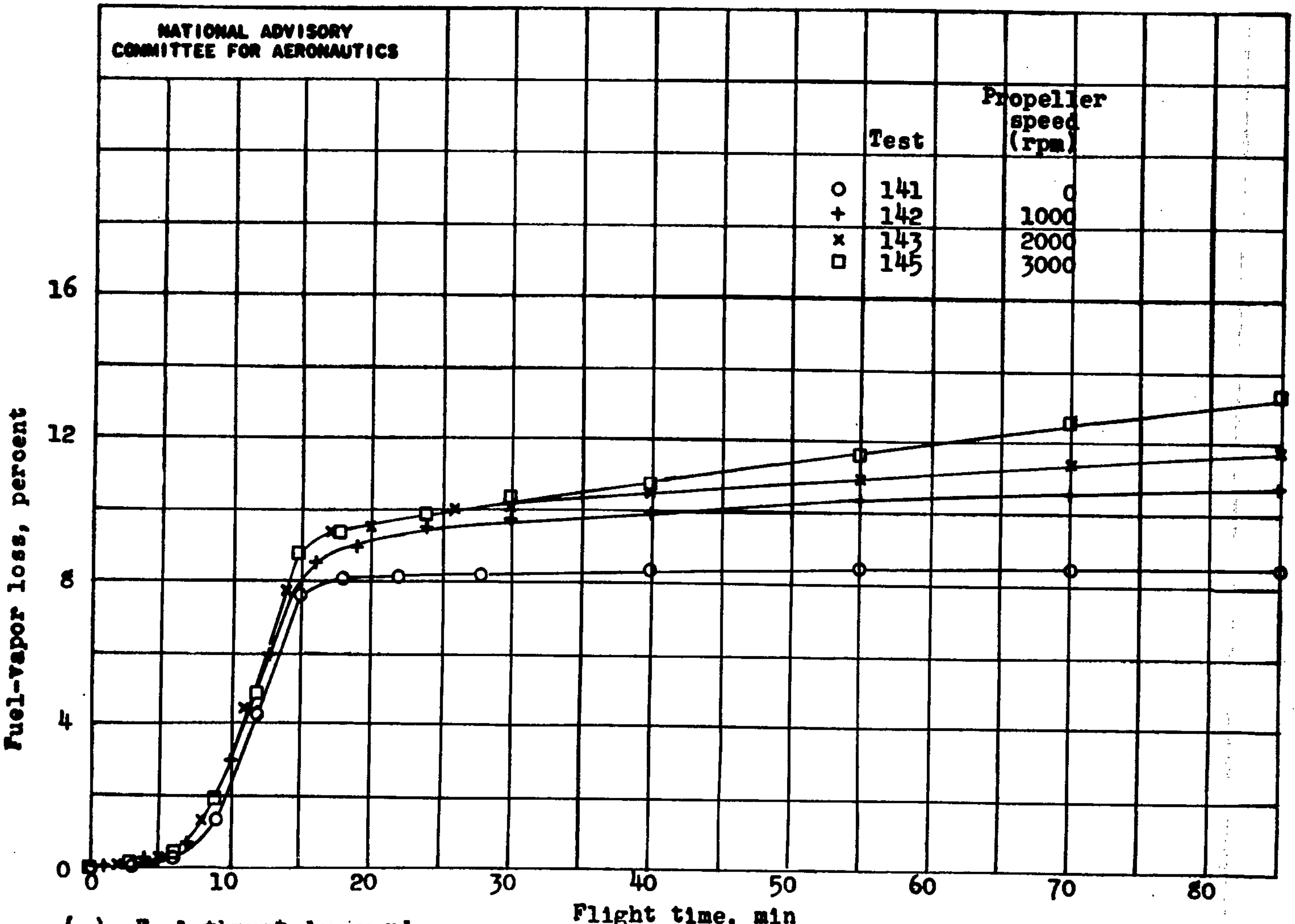
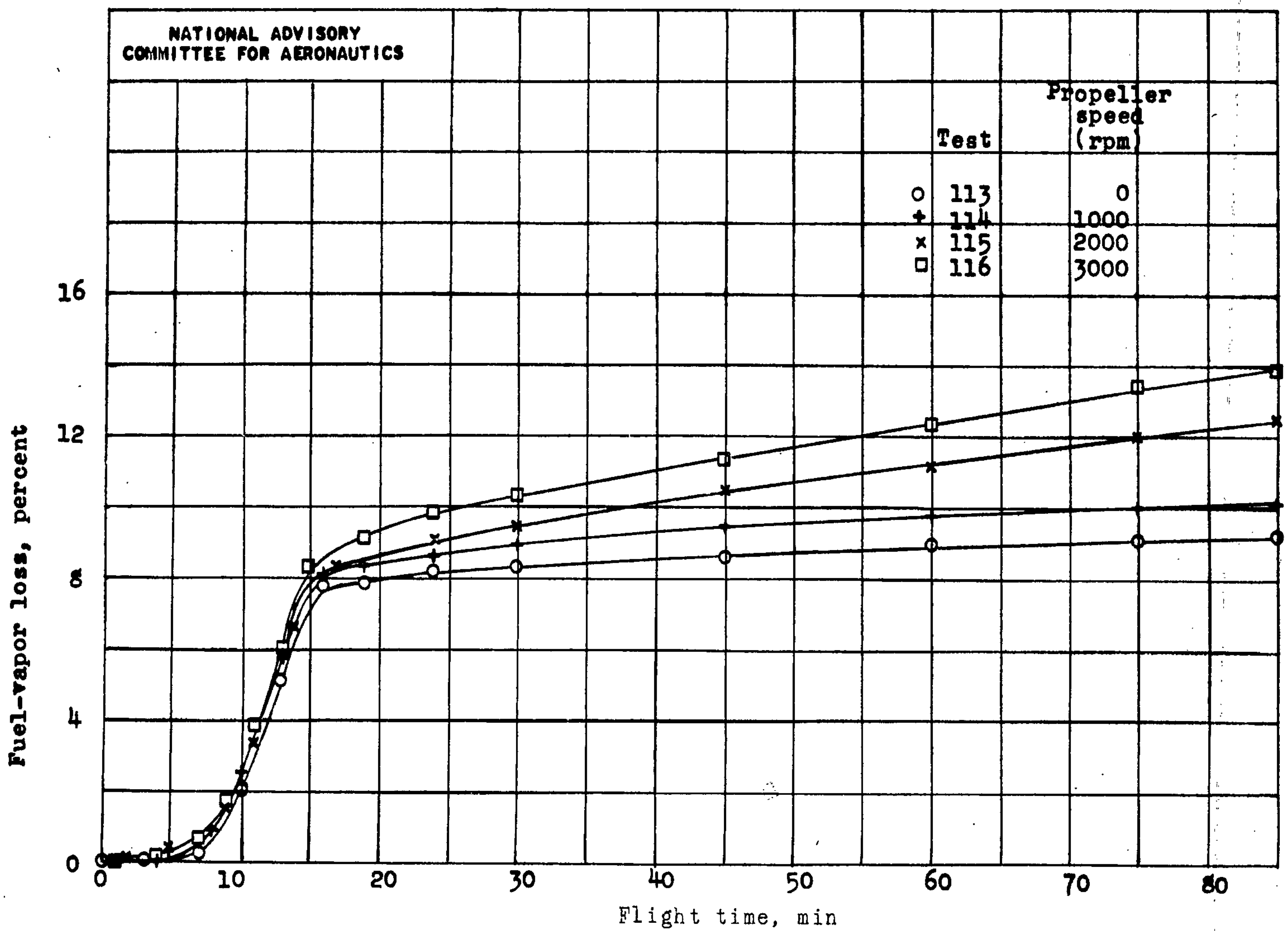


Figure 15. - Fuel-vapor loss during standard simulated flights with fuel tank vibrated.



(a) Fuel thrust downward.

Figure 16. - Fuel-vapor loss during standard simulated flights with induced fuel turbulence produced by a rotating propeller with a blade angle of 30°.



(b) Fuel thrust upward.

Figure 16. - Concluded. Fuel-vapor loss during standard simulated flights with induced fuel turbulence produced by a rotating propeller with a blade angle of 30°.

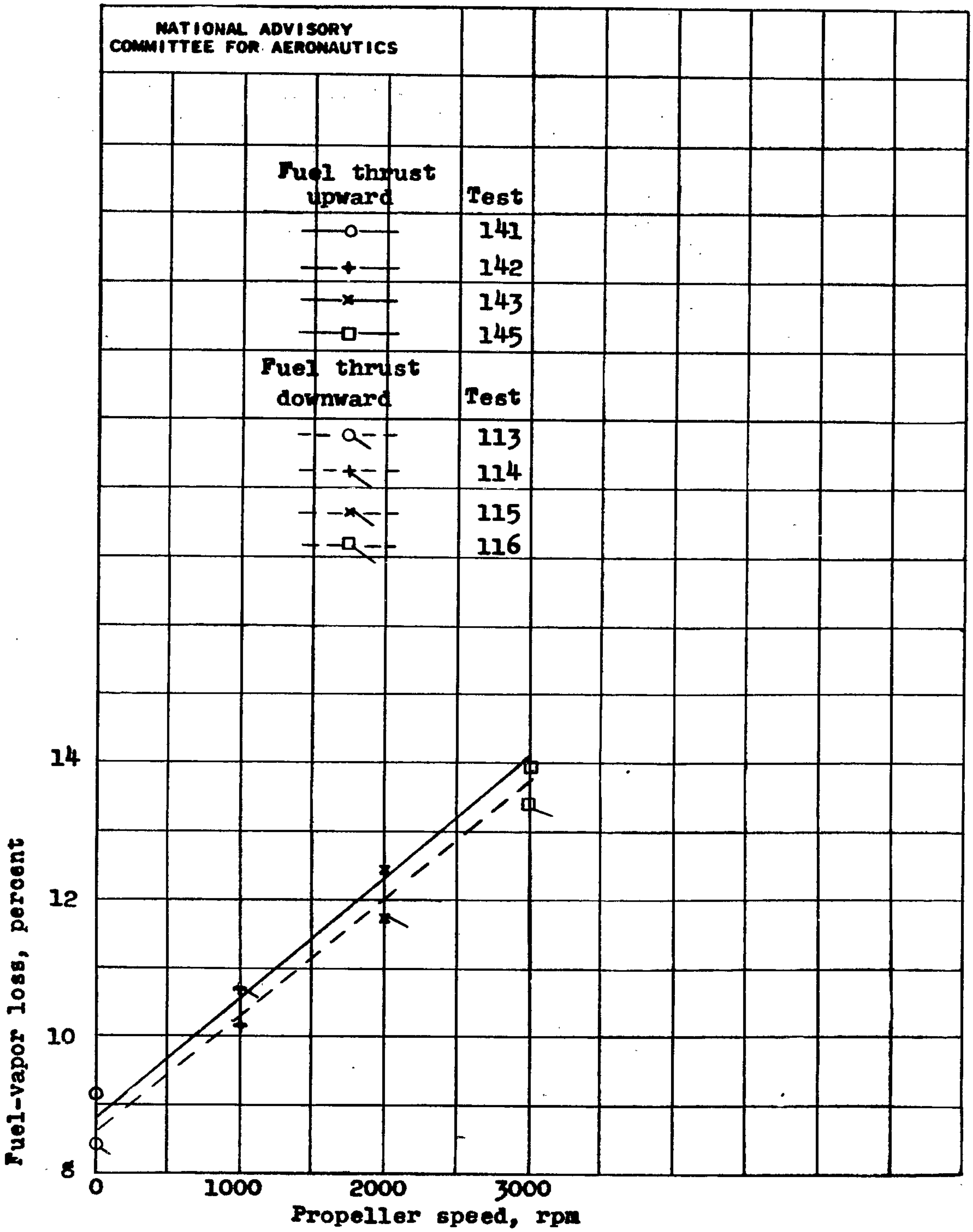


Figure 17. - Fuel-vapor loss at end of standard simulated flight with induced fuel turbulence produced by a rotating propeller with a blade angle of 30°.

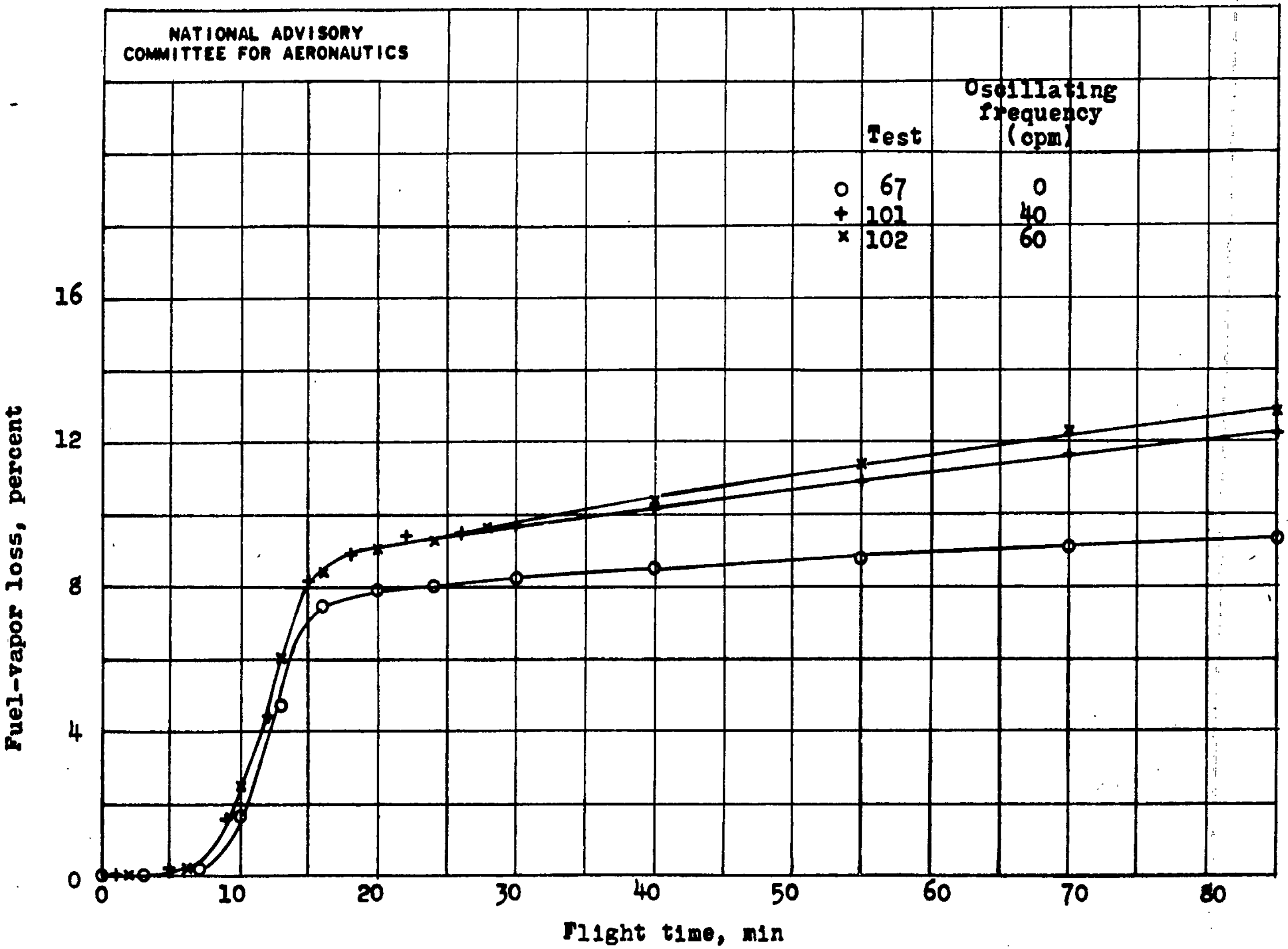


Figure 18. - Fuel-vapor loss during standard simulated flights with fuel tank oscillated through an angle of 5°.

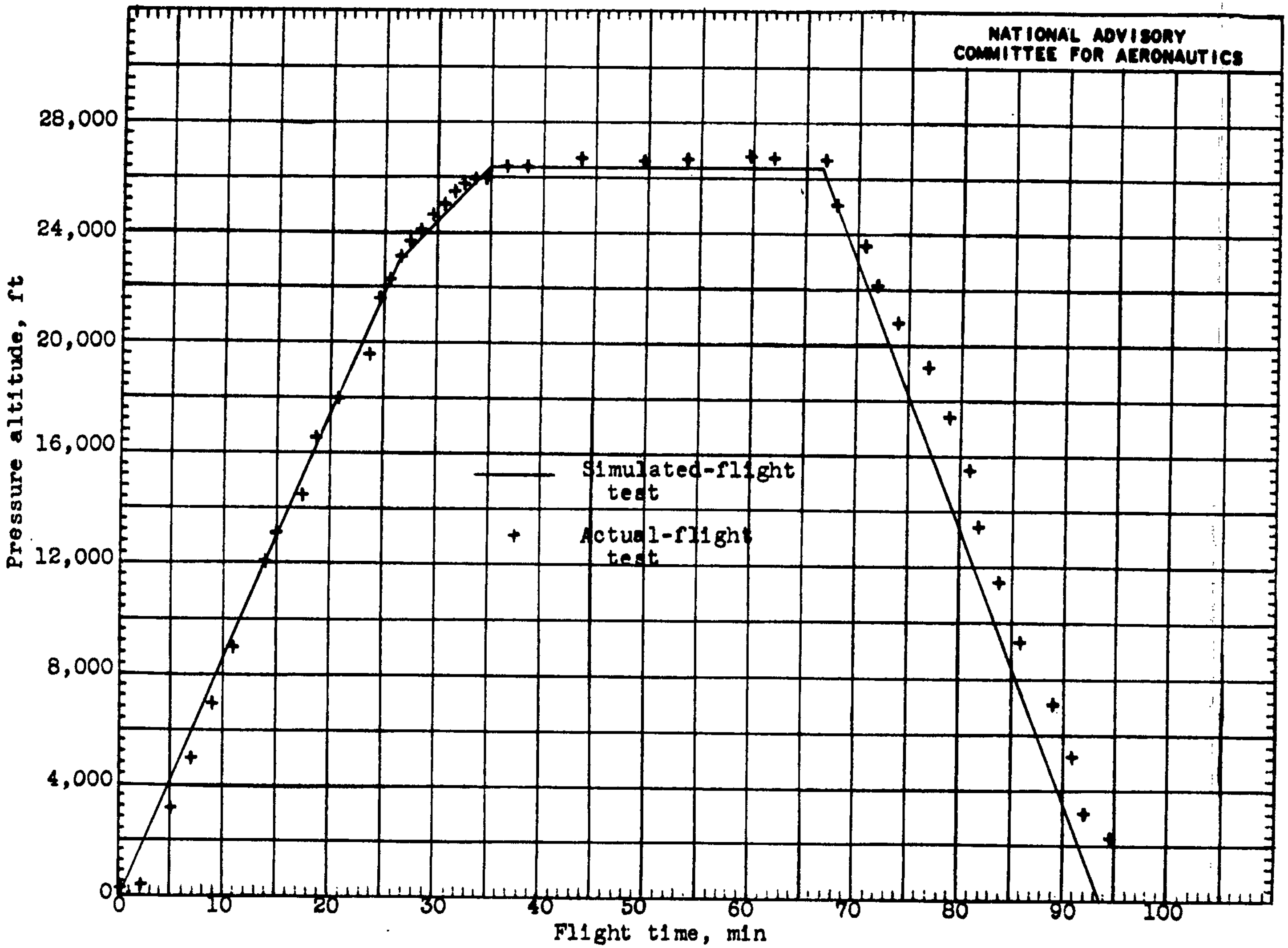


Figure 19. - Flight paths followed for both the simulated-flight and the actual-flight tests.

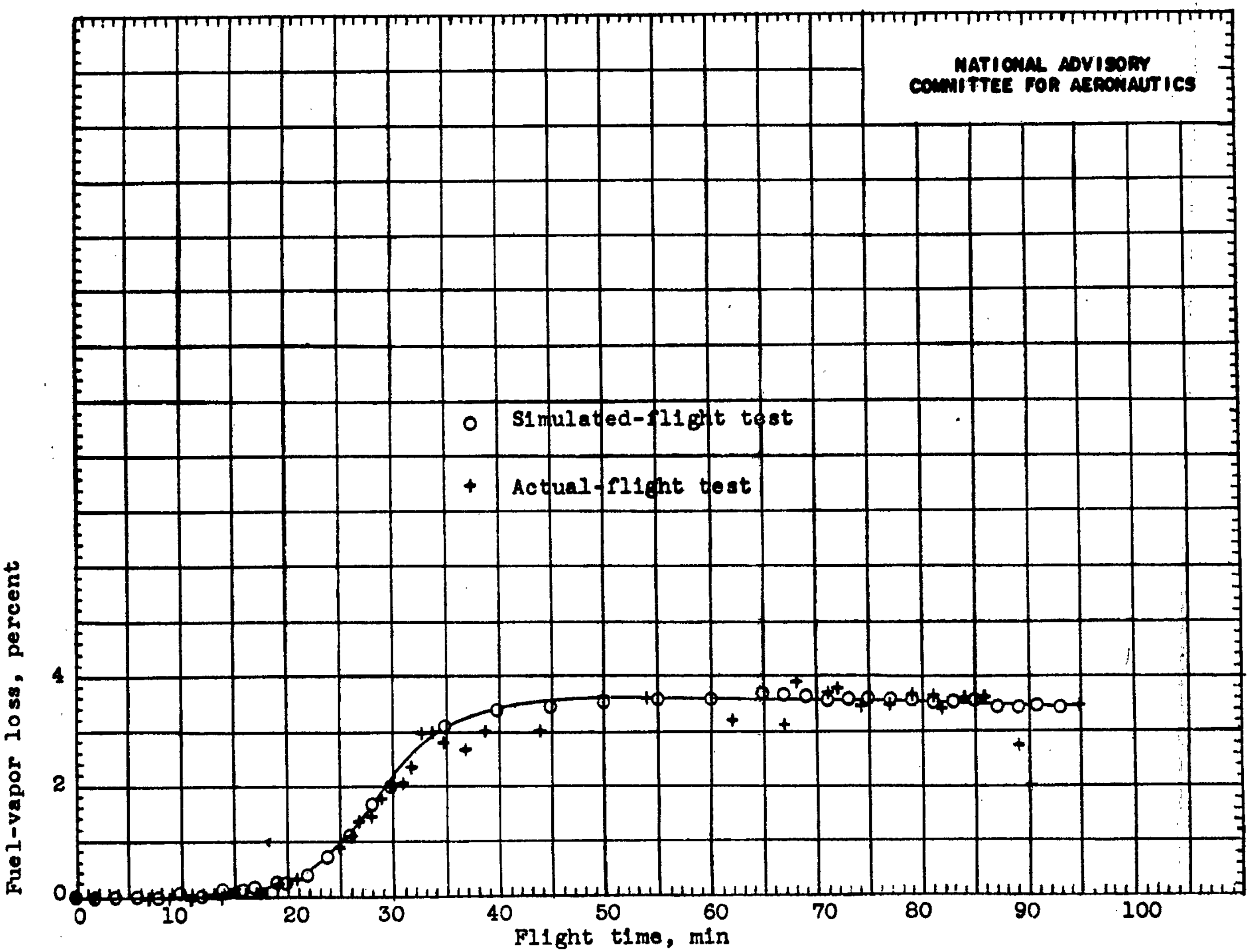


Figure 20. - Fuel-vapor loss during simulated and actual flights. Initial fuel temperature, 108° F.